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Lakes, impoundments, and reservoirs are complex environments. Many interacting factors determine water quality and recreational use potential. Each lake or reservoir is different and presents unique problems to water supply treatment operation and to full enjoyment by the public. Only through implementation of lake management strategies that include a well designed monitoring program and responsive action plan can there be optimum use of this water resource.

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Perception of Lake Water Resource Management*

Edwin E. Geldreich**

Natural lakes and impoundments of small streams are attractive environmental resources that create a demand for shared uses ranging from water supply to community development of shore lines for housing and recreational activities. Without careful management of these water resources, the desirable features may be quickly lost, the public health risk increased and the lake or impoundment transformed into an unsightly eutrophic body of water.

Management for priority needs and water quality protection is critical to achieving maximum benefits. Nationwide, natural lakes and impoundments form a very significant resource of raw water supply for public utilities. One statistical survey (1) reported that approximately 1700 municipal supplies serving more than 55 million people, or 30.6 percent of the 180 million total population served, derive all or a portion of their raw water from lakes or impoundments. Another significant point is that population growth often creates public pressure for multiple use of every lake in the surrounding region (2). Multi-use of water supply reservoirs may include hydroelectric power generation, flood control, irrigation, recreation and the aesthetic pleasures of resort development. This discussion will focus only on the latter two multi-uses.

Historically, in an effort to provide continued good quality raw source water from lakes and impoundments, many water utilities acquired large tracts

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of land on the watershed, particularly surrounding the water resource. Fences were built and the grounds patrolled to limit access to these nature preserves. In theory, the objective was to restrict human activity over the drainage basin and thereby minimize the magnitude of fecal waste released that might contain human pathogens. In practice, this vegetation buffer zone around lake shores was found to be effective in minimizing turbidity in stormwater runoff and to act as a deterrent to the rapid movement of fecal contaminants over the land surfaces during rainfall events. The net effect was to dampen water quality fluctuations which provided water characteristics that were more amendable to less complex water treatment schemes. In many instances, treatment by disinfection was the only microbial barrier employed.

As we know now, Giardia outbreaks over the past 10 years have changed forever this time-honored concept (2-6). Thousands of people became ill with giardiasis and minimal treatment barrier concepts were reevaluated for improved public health protection. The source of the pathogen was quickly found to be in the wildlife population living on the protected watershed. Beaver were most often considered to be the primary animal reservoir because of the high incidence of infection in beaver colonies and their habitat association with near-shore water environments. However, coyotes, muskrats, voles, cattle and animal pets may also be involved in the perpetuation of this pathogen in the natural environment (7, 8). Many of these animals are either part of the natural fauna or are introduced onto the watershed as domestic farm animals.

Birds and waterfowl are also sources of pollution. Sea gulls are scavengers that frequent open garbage dumps and can contribute Salmonella in their fecal droppings to lakes in coastal areas (9, 10). In one instance, sea gulls were the contributors of Salmonella to an untreated water supply reservoir in an

Alaskan community and the cause of several cases of salmonellosis (11).

Impact of Multiple Use

The quiet serenity of a sparkling lake, the breathtaking beauty of natural surroundings and the occurrence of an accessible beach brings a variety of counter pressures from people who are avid recreationists with specialized interests to open up protected water resources for multiple purpose uses. Outdoor recreational pursuits of greatest impact on the environment take on several dimensions. Perhaps, the most violent assault on protected watersheds and shore lines surrounding raw water reservoirs comes from the increasingly popular use of trail bikes, four-wheel drive vehicles and snowmobiles which enable more people to reach formerly inaccessible areas. Without careful management, such activities can destroy vegetation cover, create soil instability, generate unsightly litter and increase the threat of human wastes over the land. All of these factors will eventually have a detrimental impact on the water quality characteristics of feeder streams and runoff water that drains into the lake.

Authorization of recreational activities on a lake must include the responsibility to minimize public health risk in addition to preventing lake water quality deterioration. Statistics gathered in Georgia during 1981-1983 indicate drownings were the second most frequent cause of death from unintentional injuries (12). During that period, 249 people drowned while wading, swimming, fishing or boating (including water skiing). Where motorboating and water skiing are permitted, water use zones must be established and appropriately designated to protect bathers from boating activities that could result in serious injury or death. Turbulence created by power boats, particularly

in shallow lakes, can cause resuspension of bottom sediments that often contain viable pathogens (13). The concern is twofold; (a) introduction of resuspended pathogens and turbidity into raw water intakes for minimal water supply treatment and (b) increased risk of pathogen contact by bathers.

Designated swimming areas should have gradually sloping bottoms with no sudden drop-off that might be a hazard to non-swimmers. Beaches should be free of litter and have rodent proof litter containers (to minimize animal foraging) placed in areas of greatest use. Dogs and cats should also be prohibited because of their fecal wastes which often contain pathogens infectious to man. Defining acceptable water quality for swimming must take into consideration several aspects that are important to bathers: water clarity, water temperature, water pH, freedom from toxic chemical agents and minimal risk of contact with pathogenic organisms. While the bather can make a judgment on some of these characteristics from observations, there is no immediate perception of toxic chemical agents or waterborne pathogens that might be in an otherwise acceptable bathing water.

Swimmer illnesses associated with gastrointestinal infections produce a variety of symptoms including nausea, vomiting, diarrhea with fever, and stomach ache that is also accompanied by fever (14, 15). Pathogenic agents causing these illnesses enter the water environment through dispersion of fecal wastes discharged in domestic sewage. The pathogen concentration and types of agents in the wastewater stream are a function of the number of ill people in the community excreting specific bacterial, viral, or protozoan pathogens. Thus, it becomes essential to treat domestic wastes to achieve substantial pathogen reductions prior to release to receiving streams in the watershed. Upon entering the aquatic environment, dilution disperses the

residual population and self-purification processes may further decimate the microbial survivors before reaching the lake or impoundment.

Swimmer illnesses associated with the upper respiratory tract or with infections of ear, eye, and skin are reported to be more frequent than gastro-intestinal disturbances (16-19). These pathogenic agents are either bacterial or viral and appear to have a better correlation with staphylococci occurrences in water than with fecal indicators. This observation suggests that bather density in a swimming area is a factor for increased health risk because of more frequent contact with shedding skin bacteria among bathers in close proximity.

Excessive algal growths are troublesome in many ways. An unsightly blue-green or green color is imparted to water in which large numbers of algae are decaying. Death of an algal bloom will produce noxious odors and remove dissolved oxygen from the water, killing aquatic life in the process (20). Of greatest public health concern is the occurrence of toxic blue-green algal blooms caused by (Anabaena flos-aquae, Microcystis aeruginosa and Aphanizomenon flos-aquae). Ingestion of exotoxins released by these algae can cause illness or death in almost any mammal, bird, or fish that ingests quantities of the toxic algae. In humans, algal exotoxins cause gastroenteritis by ingestion and skin irritation through recreational body contact sports (21).

One of the most popular recreational activities associated with lakes is fishing. Owners of protected watershed lakes are often pressured by fisherman organizations to open up these resources to sport fishing. In these situations, agreements are frequently developed with local fishing interests to provide the use of the resource but only under carefully controlled stipulations. For example, the Walton, Kentucky water utility owns a small water impoundment

covering 32 acres which is fenced about 100 meters from the shoreline to restrict cattle grazing and to maintain a zone of vegetation to buffer the effects of stormwater runoff and soil erosion (22). Limited access for fishing is authorized to a private fishing club of about 250 members which leases the impoundment from the water utility. The club stocks the reservoir with pike, trout, white bone, bass, catfish, crappie and bluegill that are purchased from a commercial hatchery in Canada. Sanitary facilities to prevent waste discharges to the reservoir are provided and large containers for litter control are available around the most heavily used fishing sites. Access to the reservoir by fishermen is restricted by a guard supplied by the club during the day and by a locked gate at other times. Our observations of this type of multiple use for a water supply impoundment were very positive. Rules on litter control and the use of sanitary facilities were obeyed, probably because authorization was given to a private club that felt a sense of responsibility for the special privilege.

Residential housing development around the lake shore may introduce pollution problems arising from overloaded individual septic tanks or malfunctioning package waste treatment plants common to many small rural subdivisions. These poorly treated waste effluents not only impact on the lake water quality during periods of stormwater runoff, but may also perculate into nearby private wells used for drinking water. A brief accounting of several case histories will demonstrate the public health aspects, nationwide.

Case Histories

Pine Lake, New Jersey is a manmade impoundment that receives runoff from a 60 square mile drainage area. Housing development around the lake brought septic tanks to within 50-75 feet of the lake shore (23). Water samples from

the lake contained densities of fecal coliforms which frequently exceeded 200 organisms per 100 mL. Suspended sediment in the water correlated with the rise and decline of fecal coliform densities and was found to fluctuate with bather loads and boating activity. Fecal coliform to fecal streptococcus ratios implicated human wastes as the major pollutant although sea gull fecal wastes were also a serious problem.

Redstone Lake, Wisconsin also has a housing development around the lake (24, 25). Septic tanks along the shore line were within 100 to 1,000 feet of the lake shore. Test wells were used to monitor for pollution migration using fecal coliform, fecal streptococcus, Pseudomonas and virus measurements. Poliovirus was found within 8 days after drilling test wells located 67, 94 and 151 feet from a septic tank. At the lakeshore test well, virus was detected over a 109 day monitoring period.

Boone Reservoir, Tennessee received municipal waste considered to be treated to secondary effluent quality (26). Water quality deterioration eventually occurred and was traced to a defective outfall diffuser which permitted a sludge bank to accumulate to approximately 7 feet deep on the bottom of the reservoir over a 5 year period. This material was resuspended seasonally as a result of lake water turnovers or destratification. Fecal coliform densities reached several million organisms per 100 mL in the stratified bottom water sediment interface. Upon destratification, the sludge bank floated in the reservoir surface water and presented a health risk to water resource users. Fortunately, water supply treatment plant operations were successful in processing this poor quality raw water to meet the drinking water standards.

Lake Houston, Texas was created in 1954 by impoundment of the San Jacinto River and provides the major raw water resource for the Houston public water utility (27). The lake has a surface area of 12,765 acre (5,200 ha) and a mean depth of 12.5 ft (3.8 m). Rapid residential development along the western tributaries to the San Jacinto River created 172 small package plants for domestic waste treatment that release their effluents into the feeder streams to Lake Houston. In 1984, sanitary inspections revealed that 34 wastewater plants were in violation of the effluent quality standards. The pollution problems became most pronounced as a result of frequent storms that produce very high turbidities in the lake, sewage bypasses, and numerous overloaded septic tank effluents percolating through the soil into the lake. Consequently, water quality in the lake fluctuates drastically and bathing water quality may not meet the bacteriological standard for varying periods of time. Yearly mean fecal coliform counts near the water supply intake indicated a long term trend of deterioration in the bacteriological quality of the lake water. The use of multiple water treatment barriers, however, continues to be effective in providing a supply of safe drinking water.

Buffalo Lake, 30 miles (48 km) southwest of Amarillo, Texas, was created in 1938 by construction of an earthen dam across Tierra Blanca Creek (13). The lake is part of a national wildlife refuge with authorized recreational uses in specified areas including swimming, water skiing, fishing, boating, and camping. The lake is somewhat oblong in shape and approximately 5 miles (8 km) in length. Water depth varies from one to 2 feet (0.3 - 0.6 m) at the inflow from the creek to 10-12 feet (3-3.7 m) at the dam. The lake was formed in a broad canyon area that supports a grass-covered prairieland ecology. The drainage basin supports a human population of approximately 15,000 persons and

and a cattle feedlot population of approximately 180,000 animals. During the prevailing long dry weather periods, the natural bathing water quality in the lake was excellent. Stormwater runoff, produced by infrequent heavy thunder showers, resulted in a dramatic deterioration in water quality for feeder streams. Subsequently, there was a downstream impact on Buffalo Lake water quality resulting in fecal coliform values far in excess of 200 organisms per 100 mL. Improvements in wastewater treatment processing and use of near stream side lagoons to contain runoff from feedlots were recommended. Since the lake is shallow, it was also found desirable to restrict the horsepower and limit total number of motorboats. Furthermore, lake management was advised to continually enforce a buffer zone between the wildlife refuge area and those areas of the lake designated for swimming, wading and skiing. The concern was the potential public health risk from waterborne transmission of pathogens deposited in the sediments at the lake inlet from wildlife living in the area, cattle manure transported in feeder streams and sewage bypasses to the major stream supplying the lake.

Management Tools: Impact Assessment, Monitoring and Action Response

These case histories quickly point out the need for careful management of the water resource in an effort to provide adequate protection from a variety of contamination sources. Residential and resort housing developments always brings the threat of pollution loading to the lake or reservoir that must not be ignored (28). Waterborne viral agents originate in human fecal wastes as do various bacterial pathogens including Salmonella and Shigella. There can also be a threat from wildlife fecal pollution on a protected watershed. Wildlife is a reservoir for human pathogens that include Campylobacter, Yersinia, Giardia and Cryptosporidium. In a comparative study in

Montana, the closed or protected watershed reservoir and its associated feeder streams were found to have measurably higher densities of fecal organisms than did an open watershed that is a popular recreational and camp site area with boating, and fishing. Swimming is permitted in the reservoir itself (29). The most likely explanation is that wildlife was more abundant in the protected watershed than in the multi-use recreational watershed. Both watersheds were in the same national forest. Perhaps, there is a positive aspect to some recreational and commercial use of a watershed in that recreationists and loggers tend to discourage wildlife activity, and are more easily controlled than are beaver, muskrats and other wild animals. Other studies on recreational use of watersheds and reservoirs indicate little or no deterioration in bacterial water quality (30-35). Disregard for sanitary rules, litter control and lack of respect for utility property forced the closure of two water supply reservoirs in Massachusetts (36). In these cases, there was also some indication that the percentage of coliform occurrences in the finished water supply also decreased after the reservoirs were closed to public fishing (34), suggesting water treatment barriers were only marginally adequate.

Assessment of the environmental impact of the various intended uses of the watershed is critical to the continued useful life of the lake. Natural self-purification processes are limited in their capacity to neutralize pollutional inputs. Although storage and sedimentation often improve the chemical and bacterial quality of natural waters, there are limitations in an uncontrolled natural process that must be understood. Water intakes in stratified lakes should be adjustable to avoid near bottom zones of increased particles, accumulated decaying vegetation, stratified organic solutes and sludge banks formed by poorly operated sewage treatment plants. All of these conditions

cause an increase in the disinfection demand of water being processed into drinking water. Seasonal destratification in temperate climates causes significant changes in water quality characteristics. Upward movement of stratified anaerobic waters transports increased concentrations of sulfides, iron salts, manganese, and partially oxidized organics to water supply intakes. Many of these are associated with taste and odor problems. Resuspension of sediments also recirculates a variety of viable microorganisms including pathogens into the main body of water. Since the risk of Giardia occurrence from lakes and impoundments is an established reality, water treatment must also include filtration or some other proven process that is an effective barrier to cyst penetration into the public water supply.

The decision to permit recreational activities on a lake or reservoir must recognize an obligation to continually insure that the resource meets or exceeds recognized water quality standards for swimming. Two major threats exist: point source discharge of inadequately treated sewage effluents from small package plants and improper drainage of septic tank wastes and non-point source releases of stormwater runoff over the watershed. While the dangers associated with sewage effluents are clearly understood, the harmful qualities of stormwater are often less appreciated. Rural runoff introduces various pathogens from farm animals and wildlife fecal discharges over land surfaces, turbidity from soil erosion and a variety of chemicals including fertilizers and pesticides. These agricultural chemicals not only increase the concentration of bacterial nutrients but also the availability of nitrogen and phosphates as algal nutrients. Urban stormwater runoff contributes road salts, oils and tars, garden fertilizers and pesticides, plus fecal organisms from wildlife and animal pets.

Controlling these undesirable factors requires creation of appropriate local or regional zoning restrictions, interagency coordination and cooperation to achieve objectives, plus the development of protective laws and court support in enforcement. Critical to decision making on proposed land use, whether it involves residential or resort development, highway expansion, industrial or agricultural activities, is the environmental impact assessment. Such a fact finding analysis of the effects of a proposed use on the watershed, or on shoreland areas around the lake, is as essential as the need for impact evaluation and corrective measures to be taken for environmental damage from existing pollution problems.

Monitoring water quality is an important aspect of lake management and should include public health concerns where water supply and recreational uses are involved. Characterizing lake or reservoir water quality used in water supply treatment should specify fecal coliform and turbidity measurements made on a weekly basis. For those utilities that apply disinfection as the sole treatment process, seasonal testing for Giardia cysts should be done throughout the year. Where lakes and impoundments are located in cold water areas and disinfection is the only barrier, it would also be desirable to occasionally test for Campylobacter and Yersinia unless the disinfectant dosage or contact time is increased to compensate for seasonably colder water temperatures.

Recreational waters for swimming should be monitored on a weekly basis during the designated season and at sites within the defined bathing area. Daily sample collection should be during peak bathing periods or on days prior to holidays, weekends and following major rainfall events of one inch or more. Since the water zone of bather activity is between the shoreline

and water less than 2 meters deep, collection of samples should be made in this zone of greatest use. Three types of collections are advisable; microfilm surface layer, water at the one meter depth and bottom sediment. Collection of the microfilm of surface water is performed by dipping a sterile glass plate into the water and depositing the drainage into a sample bottle (37). The purpose of this collection and analysis is important for the detection of bather associated non-enteric pathogens. This sampling represents the streaming flow of water draining from a bather upon emergence from the water and contains the greatest densities of organisms in the water column. This water should be tested for Staphylococcus, a representative indicator of various bacteria associated with skin, saliva and mucus discharges. Recent fecal contamination from pollution plumes and resuspended sludge banks is best measured in the water column using the fecal coliform test.

Turbidity measurements may also be a useful, rapid indicator of microbial quality impacted by stormwater runoff. The decline in fecal coliform concentration is used to make a quick decision on beach openings after a closure period that was dictated by excessive fecal coliform occurrences. This application of a turbidity measurement must first be established through a study to correlate turbidity rise and decline with fecal coliform density fluctuations.

Sediment testing will supply important information on long term trends in water quality and is an excellent aquatic habitat in which to search for residual pathogen concentrations that enter the bathing water. Since microbial densities in sediments are less affected by the day-to-day fluctuations that are characteristic of the water column, these analyses may be limited to monthly intervals. Occasionally, there may be a need to identify the origins of fecal pollution entering the recreational lake. Parallel analyses for

fecal coliforms and fecal streptococci, followed by development of their density relationships, have been found to be very useful in distinguishing human pollution from sewage treatment package plants and boat sanitary wastes as contrasted to fecal wastes of other animals transported in stormwater runoff (38).

A major objective in microbiological monitoring has always been the selection of testing methods that are rapid, accurate and uncomplicated for the enumeration, isolation, and identification of primary indicator systems. While not perfect, many of the quantitative objectives are achieved by the use of either membrane filter procedures or multiple tube tests. In general, the membrane filter technique has gradually replaced the multiple tube procedure and is a more rapid and precise measure of indicator density. Water samples that are turbid from natural suspended sediments or from algal blooms may present a filtration difficulty when processing 100 mL sample volumes. In these situations it is necessary to use the less precise multiple tube procedure.

Data gathering alone will not protect public health. There must be prompt review of the laboratory information and a decision response made when water quality changes threaten the normal treatability for public water supply or signal the occurrence of bacteriological quality that does not meet standards of acceptable risk to bathers. Of the two uses of lakes and reservoirs, water supply is the more important as it impacts on every individual in the community. Adjustments in water supply treatment can be made to compensate for seasonal fluctuations in raw water quality and long term solutions sought by improvements in process control or expansion of treatment train processes. For bather protection, immediate closure of the beach with adequate public notification is the essential short term solution.

In the long term, lake management must focus on pollution prevention from point source and non-point source discharges. Quick fix solutions involving treatment of the body of water may be temporarily expedient but in the final analysis may prove not to be cost effective or may even be destructive to the complex biota living in this fragile water environment. Some of these practices include alum treatment for removal of phosphates for algae control (39), copper sulfate additions to suppress algal blooms (40), chemical neutralization (liming) strategies for renovating acid stressed lakes (41), aeration to improve dissolved oxygen dynamics in stratified lakes (42), and powdered carbon application for taste and odor improvement in water supply reservoirs (43). While these treatment practices are effective when properly managed, there are some undesirable trade-offs. Insoluble treatment additives accumulate with time on the lake bottom and create a reduction in water containment capacity. Resuspension of coagulant sludges by destratification, wave action or high power boating activity will reintroduce microorganisms entrapped in flocculated particles to the water column (13, 44). Some soluble additives such as copper sulfate and aeration may adversely effect food chain organisms and fish populations (40).

Summary

In summary lakes, impoundments, and reservoirs are complex environments. Many interacting factors determine water quality and recreational use potential. Each lake or reservoir is different and presents unique problems to water supply treatment operation and to full enjoyment by the public. Only through implementation of lake management strategies that include a well designed monitoring program and responsive action plan can there be optimum use of this water resource.

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